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Fatigue experiment of stud welded on steel plate for a new bridge deck system

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Abstract. This paper presents push-out tests of stud shear connectors to examine their fatigue behavior for developing a new composite bridge deck system. The fifteen push-out specimens of D16 mm stud welded on 9 mm steel plate were fabricated according to Eurocode-4, and a series of fatigue endurance test and residual strength test were performed. Additionally, the stiffness and strength variations by cyclic loading were compared. The push-out test, when the stiffness reduction ratio of the specimens was 0.95 under cyclic load, resulted in the failure of the studs. The stiffness variation of the push-out specimens additionally showed that the application of cyclic loads reduced the residual strength. The fatigue strength of the shear connectors were compared with the design values specified in the Eurocode-4, ASSHTO LRFD and JSSC codes. The comparison result showed that the fatigue endurance of the specimens satisfies the design values of these codes.

Keywords: stud shear connector; fatigue behavior; fatigue endurance; residual strength; composite bridge deck system.

1. Introduction

Steel–concrete composite structures have been widely used for their economy in combining the high strength of steel with the stiffness and compressive strength of concrete. Among steel–concrete composite structures, steel–concrete composite deck systems are used in the construction of buildings and highway bridges (Oehlers and Bradford 1999, Johnson 1994). To achieve the desired composite action in a composite bridge deck, the longitudinal shear force needs to be transferred between the steel plate and the concrete. Shear connectors are used to provide composite action at the composite interface. Head-stud shear connectors are the most common type of shear connectors used in composite structures. Since the early 1950s and experimental confirmation by Viest *et al*. of shear connectors for composite structures, research on stud shear connectors has been conducted worldwide (Johnson 2000, Viest 1956 1960, Oehlers and Foley 1985, Oehlers and Johnson 1987, Ellobody and Lam 2002, Shim *et*

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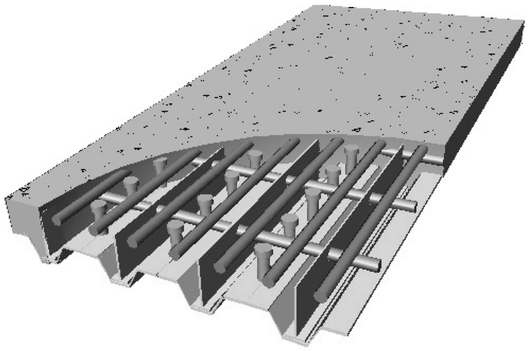


Fig. 1 Schematic of composite deck profile

al. 2003, Hanswille *et al*. 2007). Despite the different testing arrangements in previous studies, current design codes disregard the differences of different test arrangements and the combination of their results. Therefore, a standard push-out specimen was proposed in Eurocode-4 (Eurocode-4 ENV 1997).

This study aims to acquire a fundamental data regarding the fatigue behavior of D16 mm stud, in development of a new steel-concrete composite bridge deck system illustrated in Fig. 1 (Jeong 2004, Jeong *et al*. 2005, Korea Institute of Construction Technology 2005). Fifteen push-out specimens were fabricated according to the Eurocode-4 to evaluate the fatigue behavior of D16 mm stud welded on a 9 mm steel plate used in the new bridge deck system. Push-out tests including fatigue endurance test and residual strength test were carried out, from which the variation in the stiffness and strength under cyclic loads were evaluated. The fatigue strength was also compared with the fatigue design codes in Eurocode-4, JSSC, and AASHTO LRFD (Eurocode-4 ENV 1997, The JSSC 1993, AASHTO LRFD 2004).

2. Fatigue strength and fatigue design codes of stud shear connector

The fatigue resistance of a shear connector is evaluated by an endurance-based test and a residual strength-based test. An endurance-based test evaluates the fatigue strength of a shear connector by applying a load at a constant loading range repetitively until failure occurs, where the fatigue strength is determined by the cycle of fatigue load, and is expressed by an S–N curve. A residual strength-based test applies a constant load to specimens repetitively in specific cycles and evaluates their static shear strength. It is difficult to evaluate the residual strength of a shear connector where the fatigue load has been applied by means of a fatigue endurance test, owing to a shortage of data on the condition of shear connectors damaged by fatigue. Generally, the residual strength of shear connectors is evaluated by means of a static test after applying a fatigue load with a constant stress.

Various design equations of the fatigue strength of a stud are presented according to the individual design codes of each country. In Eurocode-4, the fatigue strength of an automatically welded head-stud connector in the normal-weight aggregate with normal welding parts shall be taken as Eq. (1) (Eurocode-4-1-7 ENV 1997), where N_R is the number of stress range cycles, m the slope of the fatigue strength curve (m=8), and a the constant according to the slope and characteristic fatigue strength, with the value $\log a = 22.123$.

$$\log N_R = \log a - m \log \Delta\tau_R \qquad (1)$$

In AASHTO LRFD, the fatigue strength of the stud connector shall be taken as Eq. (2) (AASHTO LRFD 2004), whereas the Japanese Society of Steel Construction categorizes the fatigue of the stud connector as *S*, the fatigue category, which shall be taken as Eq. (3) (The JSSC 1993).

$$\Delta\tau_R = \frac{4}{\pi}a = 303 - 37.6\log N_R \tag{2}$$

$$\log N_R = 15.816 - 5\log\Delta\tau_R \tag{3}$$

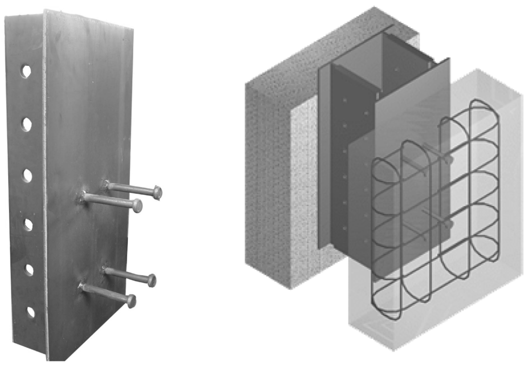
3. Fatigue push-out test

3.1 Push-out specimen

In this study, to evaluate the fatigue behavior and fatigue strength of a D16 mm stud connector used in steel–concrete composite bridge decks, a total of fifteen specimens were fabricated according to the standard push-out test specimen in Eurocode-4. The specimens were 700 mm long, 600 mm wide and 211 mm thick concrete slabs. The concrete slabs were connected to 9 mm steel plates by means of four welded stud shear connectors 16 mm in diameter and 125 mm in height. The design strength of the concrete was 30 MPa. The dimensions of the specimens were identical so as to better evaluate the behavior of the shear connectors due to fatigue.

Bonding at the interface between the steel plate and the concrete slab was prevented by applying grease. Each of the concrete slabs was cast in a horizontal position, as is done for composite bridge decks, and air-cured. Two pieces of the composite specimens were independently cast and cured in a horizontal position, and then were connected by bolting and held vertically.

Fig. 2(a) shows the stud shear connector welded on the steel plate. The width of the plate is the same as that of a wavelength of the corrugated steel plate in the new bridge deck system (Jeong *et al*. 2005, Jeong 2004, KICT 2005). Fig. 2(b) is a sketch of the push-out test specimens. From a test fabrication of the new bridge deck system, it was found that the transverse reinforcement can cause compaction problems when pouring of the concrete and modification is being made to the design. The transverse reinforcement was placed as it is in the new design of the new bridge deck system. Fig. 3 is a detail of the specimens. The push-out test specimens are summarized in Table 1. In the notations accompanying



(a) (b)

Fig. 2 Push-out specimen: (a) Stud connector welded on steel plate, (b) Sketch of push-out specimens

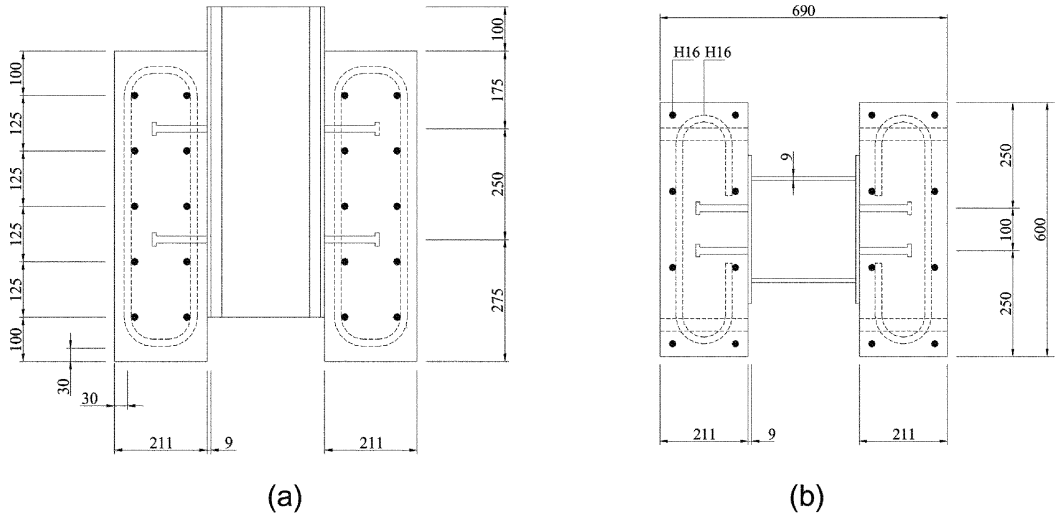


Fig. 3 Details of push-out specimen (units: mm): (a) Front view, (b) Plan view

Table 1 Types and characteristics of the push-out specimens

Specimens	Test	Stress range(MPa)	Numbers of fatigue load
ST-S-A1		-	-
ST-S-A2	Static	-	-
ST-S-A3		-	-
ST-F-A1		100	up to failure
ST-F-A2		100	up to failure
ST-F-A3		100	up to failure
ST-F-B1		130	up to failure
ST-F-B2	Fatigue (Endurance)	130	up to failure
ST-F-B3		130	up to failure
ST-F-C1		150	up to failure
ST-F-C2		150	up to failure
ST-F-C3		150	up to failure
ST-R-A1		100	500,000
ST-R-A2	Fatigue (Residual strength)	100	1,000,000
ST-R-A3		100	1,500,000

the specimens, A, B and C indicate the stress range, 100, 130 and 150 MPa respectively, employed in the fatigue endurance tests. S, F and R represent the types of tests: static, endurance, and residual strength.

3.2 Material properties and test program

The stud shear connector used in this test was made of SS400 grade steel (Ministry of Construction and Transportation, Korea 2005). The material properties of the stud were measured by a tensile

Table 2 Material properties of stud connectors

Specimens	Yield stress (MPa)	Tensile stress (MPa)	Elongation (%)	Young's modulus (MPa)
S1	352	424	33	2.13×10^5
S2	353	431	34	2.13×10^5
S3	348	412	34	2.13×10^5

Table 3 Material properties of concrete

Testing time	Compressive strength (MPa)
Design strength	30.0
28days (standard curing)	32.1
At the time of static test (air curing)	33.3
At the time of fatigue test (air curing)	34.7

strength test: the determined yield stress was 351 MPa, the tensile strength was 422 MPa, and the elongation of the stud was about 34%. These results are summarized in Table 2.

The concrete used in the specimen was coarse aggregate with a maximum grade of 25 mm, a design strength of 30 MPa, and a slump of 120 mm. Concrete cylinders, used to determine compressive strength, were prepared at the time of casting the push-out specimens and cured under a condition similar to that of the specimens. One set of specimens was cured according to the standard and the others were cured alongside the push specimens. The concrete strengths were measured on the day of testing, and the results are listed in Table 3.

Static and fatigue loading were applied respectively using a static loading actuator of 2,000 kN capacity and a fatigue loading actuator of 1,000 kN capacity. Four LVDTs were installed to measure the relative-slip on each steel plate to which the studs were welded, as shown in Fig. 4. Static loading for static and residual strength was applied using a displacement control at a speed of 0.05 mm/sec. Fatigue

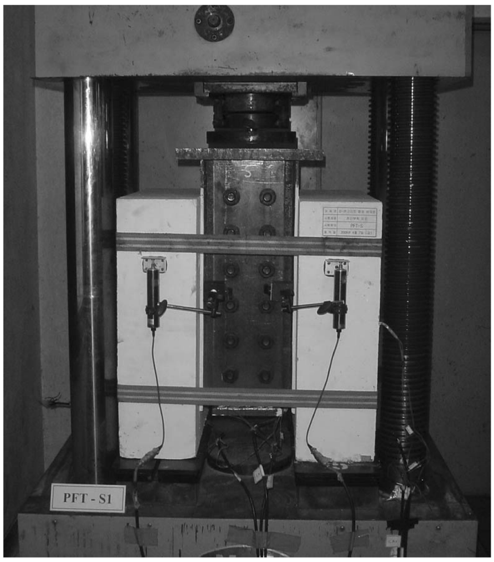


Fig. 4 Push-out test set-up

loading for the fatigue endurance and residual tests was applied with a frequency of $f = 6.0$ Hz. To verify the relative displacement and stiffness variation of the shear connector according to fatigue loading, 150 kN, about 20% of the static strength, was applied to every cycle loading of 50,000 until fatigue failure. In addition, the maximum fatigue loading for the endurance test was set to 60% or less of the static strength (Johnson 2000), so that all of the fatigue loading, applied to the fatigue testing of the stud shear connector, could be within the elasticity limit. The minimum fatigue loading was set to 20% of the maximum load.

Fig. 4 shows the static test of the shear connector. Ties were set up at the top and bottom of the specimens to prevent a sudden separation of the steel and the concrete slab resulting from the failure of the specimens.

4. Results of push-out test

4.1 Static strength test

Table 4 shows the ultimate strength and the relative-slip to ultimate strength in the static strength tests. The all three specimens showed similar results for ultimate strength. Shank failure was detected on the shear connector and the failure modes were all similar. The average of the ultimate strength and the relative-slip to ultimate strength from the static strength test was 788.9 kN and 8.47 mm, respectively.

Fig. 5 represents the load/relative-slip curve from static strength tests. When a shear load is applied to a stud shear connector, the bearing zones that are closest to the applied area will resist first. As the load

Table 4 Results of static strength test

Specimens	Ultimate strength (kN)	Ultimate strength/Relative-slip (mm)	Failure mode
ST-S-A1	779.2	8.66	Shank failure
ST-S-A2	804.5	7.64	Shank failure
ST-S-A3	783.1	9.12	Shank failure
Average	788.9	8.47	-

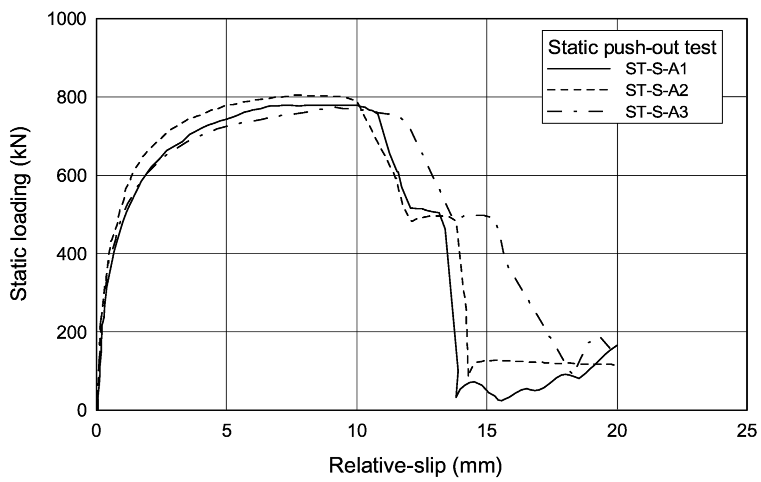


Fig. 5 Load/relative-slip curve

Table 5 Fatigue load range

Stress range (MPa)	Fatigue load range(kN)		Stress ratio
	Minimum loading	Maximum loading	
100	39.4	197.0	$\frac{\sigma_{max}}{\sigma_{min}} = 5.0$
130	51.2	256.1	
150	59.1	295.5	

increases, relative-slip of the shear connector as well as plastic deformation of the concrete occurs. As shown in Fig. 5, the load/relative-slip relation increased linearly up to 60% of the maximum loading. When the loading was increased further, the relative-slip also increased remarkably, and the stud shear connector failed.

The fatigue load range in fatigue testing is determined from the static test results and presented in Table 5. In order for the stress range of the stud according to the fatigue load to be within the limits of elasticity, the maximum fatigue load was limited to 60% or less of the static ultimate strength, and the minimum fatigue load was set to 20% of the maximum load.

4.2 Fatigue strength test

4.2.1 Fatigue endurance test

Table 6 presents a summary of the fatigue tests at each stress level according to stress range and fatigue endurance. Fig. 6 shows the fatigue failure modes of a stud shear connector.

Figs. 7~9 show the load/relative-slips according to the fatigue loading. The figures show an increase in relative-slip with an increase in the amount of fatigue load. Such a relative-slip indicates that stress is concentrated on the concrete on the lower part of the shear connector, leading to the gradual crushing of the bearing zone. Once concrete deformation initiated, the stud shear connector began to deform. It caused the relative-slip to increase gradually until just before fatigue failure, at which point relative-slips increased rapidly and strength decreased sharply.

Figs. 10~12 show the variation in relative-slip according to the fatigue load as measured on log and normal scales. As in Figs. 7~9, the number of the fatigue load is shown to increase the relative-slip. Just before fatigue failure, moreover, relative-slip increases rapidly. In particular, when the fatigue stress range is 100 MPa and fatigue load is 1.0×10^6, 130 MPa and 2.0×10^5, and 150 MPa and 1.0×10^5, the

Table 6 Results of fatigue endurance test

Specimens	Stress range (MPa)	Numbers of fatigue loading(N)	Failure mode
ST-F-A1	100	2,120,000	Shank failure
ST-F-A2		2,535,490	Shank failure
ST-F-A3		2,828,560	Shank failure
ST-F-B1	130	656,880	Shank failure
ST-F-B2		735,740	Shank failure
ST-F-B3		1,300,800	Shank failure
ST-F-C1	150	231,580	Shank failure
ST-F-C2		274,440	Shank failure
ST-F-C3		161,430	Shank failure

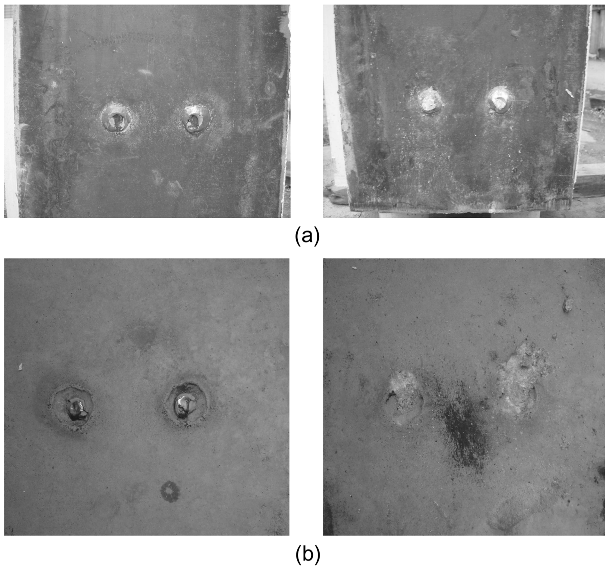


Fig. 6 Fatigue failure modes of specimen (ST-F-A1): (a) Steel, (b) Concrete slab

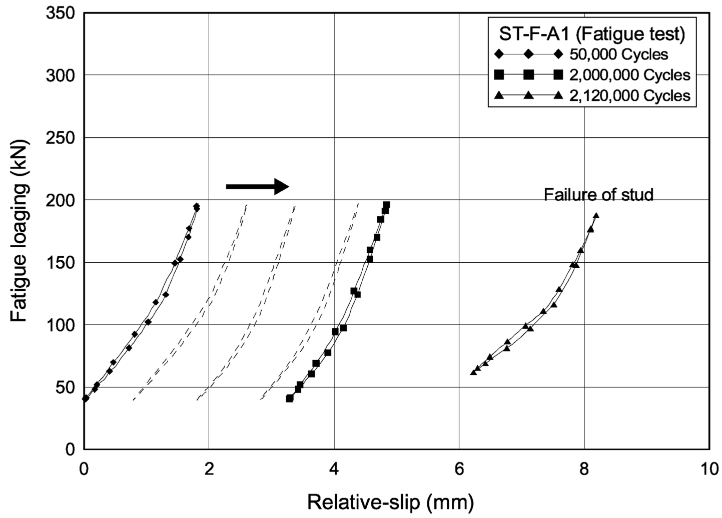


Fig. 7 Stress range 100 MPa (ST-F-A1)

slope of the log scale curve changes remarkably. In addition, the increase in the stress range increases the maximum load of the stress range. Accordingly, the relative-slip increases.

The sharp increase in relative-slip becomes even faster when the stress range increases. This is explained by the fact that fatigue endurance is relatively lower in a higher stress range than in a lower stress range. Also, the zone where relative-slip increases slowly indicates that partial damage occurs in the concrete bearing zone close to the shear connector, whereas the rapid increase in relative-slip indicates that the fatigue cracks have occurred and are spreading in the stud shear connector.

When evaluating damage to the stud shear connection in a fatigue test, one can verify the residual relative-slip or compare the maximum relative-slip under the identical load. Fig. 13 presents the results

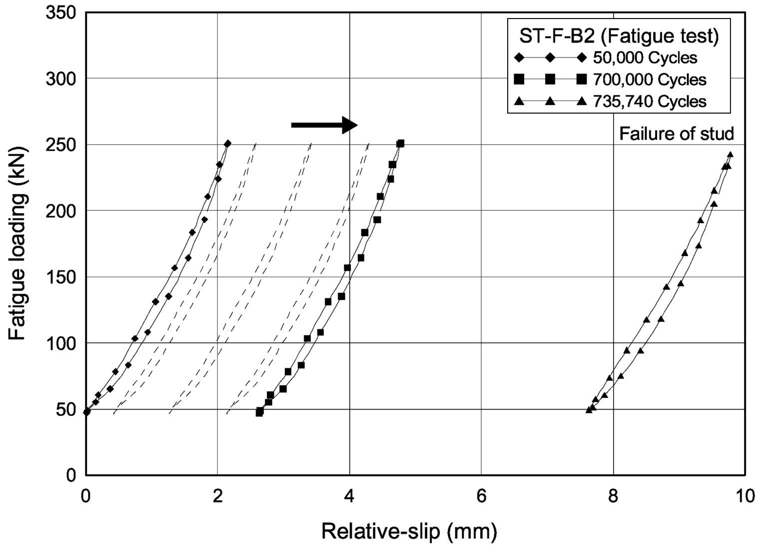


Fig. 8 Stress range 130 MPa (ST-F-B2)

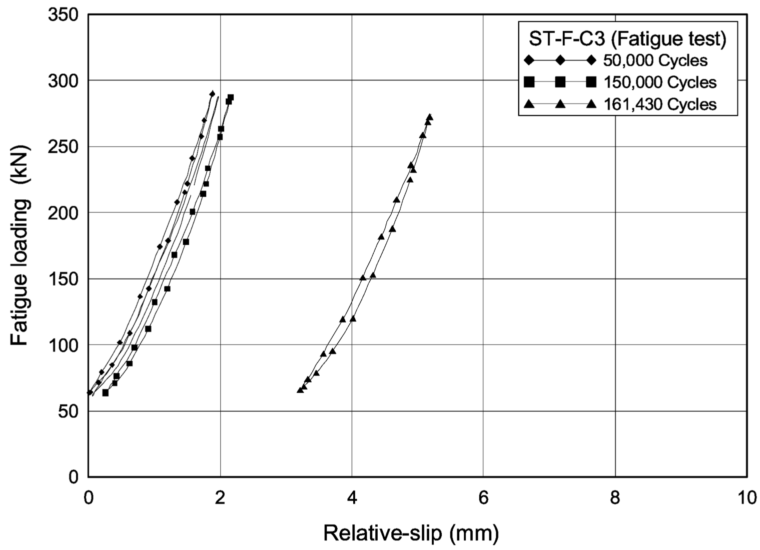


Fig. 9 Stress range 150 MPa (ST-F-C3)

in log and normal scale curves by normalizing the relationship between the load and the relative-slip according to the fatigue damage on the stud shear connector, as shown in Figs. 10~12.

In the case of 130 MPa and 150 MPa shown in Fig. 13, the ratio of the stiffness variation decreased to 0.95 or less, and then fatigue damage to the stud shear connector occurred. In the case of 100 MPa, stiffness variation due to fatigue damage did not occur until fatigue loading was repeated by 1.5×10^6 cycles. However, the stiffness continued to decrease, and after falling to 0.95 or less, fatigue failure of the shear connector occurred. Furthermore, the larger the stress range of fatigue load, the greater the decrease of stiffness due to fatigue loading became. Therefore, the variation of stiffness due to fatigue load is evaluated the fatigue failure of the stud shear connector, which in this study is at the 0.95 level of static stiffness.

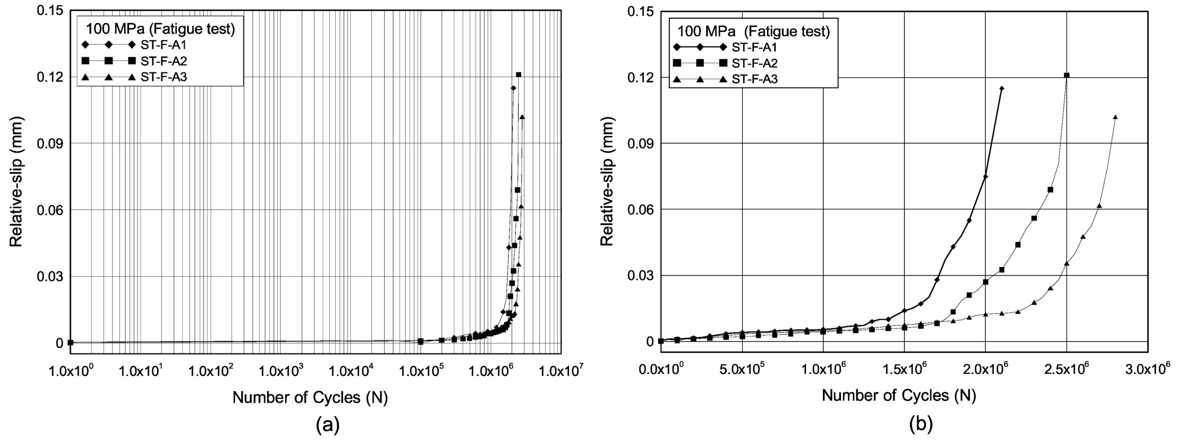


Fig. 10 Relative-slip variation (stress range 100 MPa): (a) Log scale, (b) Normal scale

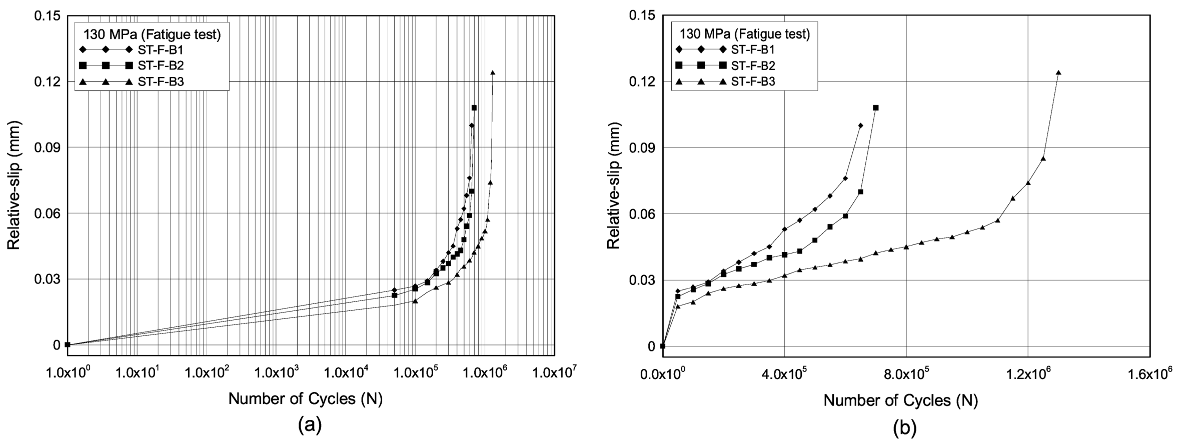


Fig. 11 Relative-slip variation (stress range 130 MPa): (a) Log scale, (b) Normal scale

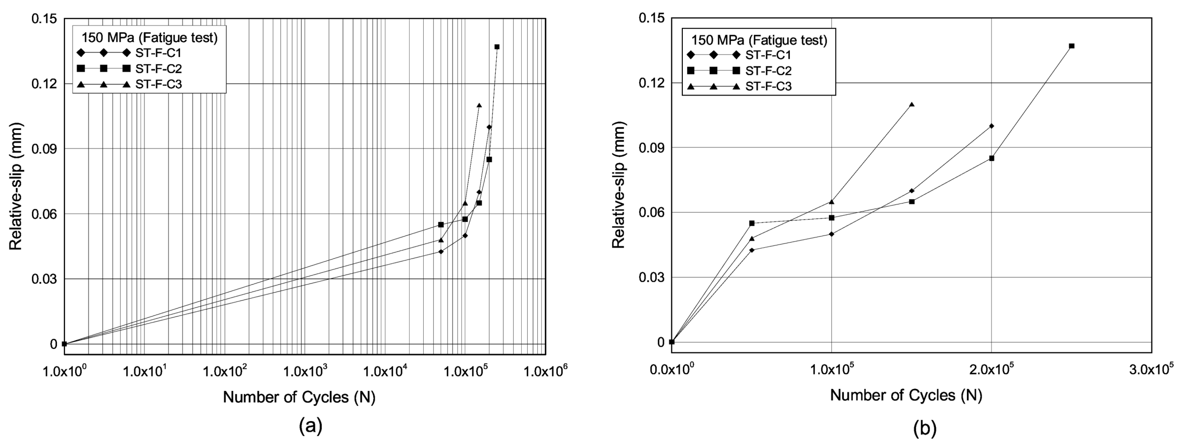


Fig. 12 Relative-slip variation (stress range 150 MPa): (a) Log scale, (b) Normal scale

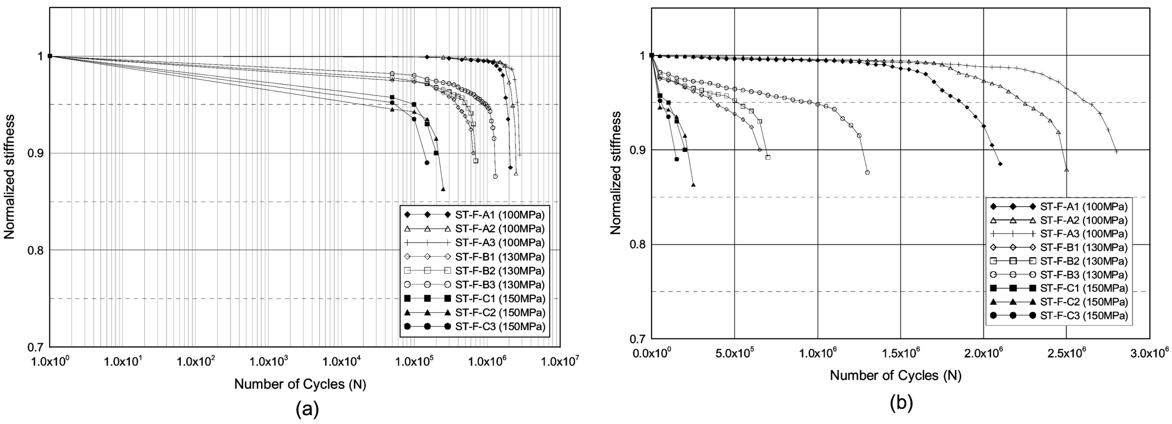


Fig. 13 Stiffness variation of head-stud shear connectors: (a) Log scale, (b) Normal scale

Table 7 Results of residual strength test

Specimens	Stress range (MPa)	Numbers of fatigue loading	Ultimate strength (kN)
ST-S-A1	×	×	779.2
ST-S-A2	×	×	804.5
ST-S-A3	×	×	783.1
ST-R-A1	100	500,000	716.4
ST-R-A2	100	1,000,000	690.5
ST-R-A3	100	1,500,000	620.6

4.2.2 Residual strength test

Table 7 presents the results of a residual strength test of fatigue loading with 100 MPa of the stress range each from 5.0×10^5 cycles, 1.0×10^6 cycles, and 1.5×10^6 cycles. The load–slip curve comparing the residual strength test and the static test results is expressed in Fig. 15. The results of the residual strength test show that in the case of 5.0×10^5 cycles and 1.0×10^6 cycles, little change occurred in strength. Compared with the results of the static test, the decrease in strength in the case of 5.0×10^5 cycles was about 9.2%, whereas in the case of 1.0×10^6 cycles it was about 12.5%. However, comparing these two cases with that of 1.5×10^6 cycles, the decrease in specimen stiffness was greater, and the decrease in strength about 21.3%. Compared with the stiffness variation due to fatigue loading results shown in Fig. 13, this means that the bigger the variation in stiffness, the bigger the change in strength. As the concrete bearing zone increases with fatigue load, the size of relative-slip also increases, and residual strength decreases accordingly. Fig. 16 shows the results of the residual strength test together with the results of the static strength test and fatigue endurance test for the stress range of 100 MPa.

4.2.3 S-N curve

Table 8 and Fig. 16 show the comparison between the fatigue test results and design values according to Eurocode-4, AASHTO LRFD, and JSSC codes. From a linear interpolation analysis of the test results, the slope of the S-N curve and the mean value of the fatigue strength corresponding to 2.0×10^6 cycles are $m = 7.5$ and $\Delta\tau_C = 106.5$ MPa. Additionally, the slope of the Eurocode-4 curve and the characteristic fatigue strength corresponding to 2.0×10^6 cycles are $m = 8$ and $\Delta\tau_C = 90$ MPa, whereas those of JSSC are $m = 5$ and $\Delta\tau_C = 80$ MPa. The fatigue test results show that the fatigue endurance of

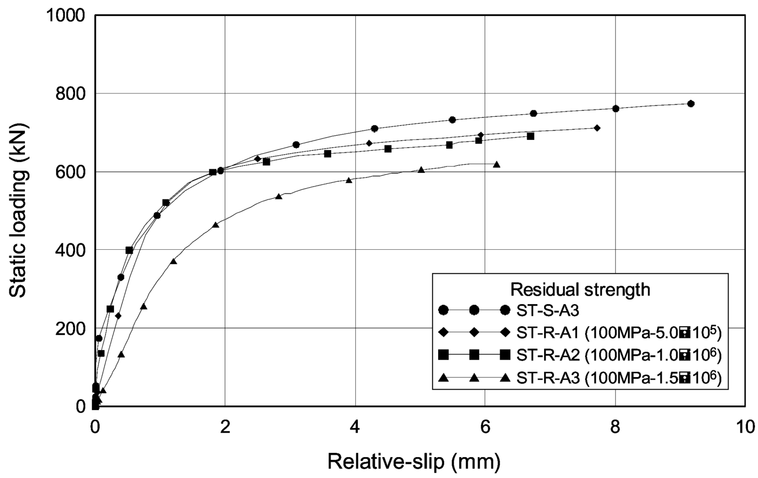


Fig. 14 Load/relative-slip curve of residual strength test

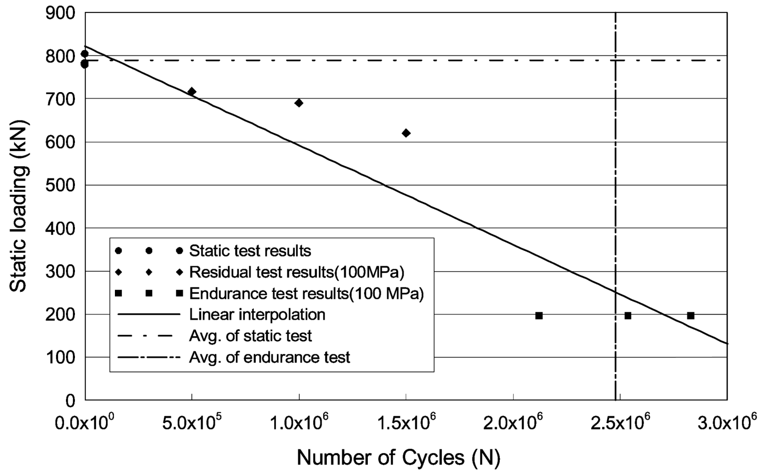


Fig. 15 Residual strength

Table 8 Comparison of fatigue endurance test results and present design codes

Specimens	Stress range(MPa)	Failure (N)	Log(N)/Log(N_R)		
			Eurocode-4	AASHTO LRFD	JSSC
ST-S-A1		2,120,000	1.03	1.16	1.09
ST-S-A2	100	2,535,490	1.04	1.18	1.10
ST-S-A3		2,828,560	1.05	1.19	1.11
ST-F-B1		656,880	1.11	1.25	1.11
ST-F-B2	130	735,740	1.12	1.27	1.12
ST-F-B3		1,300,800	1.17	1.32	1.17
ST-F-C1		231,580	1.13	1.31	1.09
ST-F-C2	150	274,440	1.15	1.32	1.10
ST-F-C3		161,430	1.10	1.27	1.06

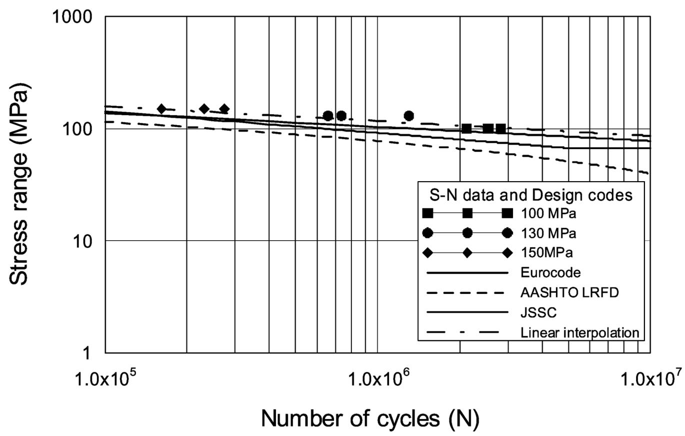


Fig. 16 S–N curve

D16 mm shear connectors used in the new bridge deck system satisfies the design values of the Eurocode-4, JSSC and AASHTO LRFD. Here, *m* is the slope of the fatigue strength curve and $\Delta\tau_C$ is the reference value at 2.0×10^6 cycles.

5. Conclusions

This study evaluated the fundamental fatigue behavior of D16 mm stud shear connectors welded on 9 mm steel plate for developing the new composite bridge deck system. The fifteen push-out specimens used in the study were fabricated according to Eurocode-4, and were subjected to fatigue endurance and residual strength tests. The following conclusions were obtained.

1. The fatigue test of the stud shear connector showed that, according to fatigue loading cycles, stress was concentrated on the concrete bearing zone in the lower part of the shear connector, resulting in the plastic deformation of the concrete. This caused the deformation of the stud shear connector, which increased the relative-slip of the steel and concrete slab. This relative-slip increased rapidly just before fatigue failure, after which the stiffness rapidly decreased.
2. The larger the stress range, the greater the maximum fatigue load in the given stress range, which increased the relative-slip. The increase in the stress range of the fatigue load accelerated to the point at which the relative-slip also rapidly increased, indicating that fatigue endurance for the higher stress range was relatively lower than for the lower stress range. Additionally, it was shown that in the variation of the stiffness of the stud shear connector, which was evaluated according to the relative-slip, about 0.95 of the normalized stiffness value rapidly increased the fatigue damage to the stud shear connector, causing fatigue failure.
3. The residual strength test showed that, in the case of 5.0×10^5 cycles and 1.0×10^6 cycles, there was little change in stiffness. However, about 9.2% and 12.5% of the decrease in strength, respectively, occurred after 5.0×10^5 and 1.0×10^6 cycles of fatigue loading. In the case of 1.5×10^6 cycles of fatigue loading, by contrast, the initial stiffness decreased greatly, while the residual strength decreased by about 21.3%. This means that the greater the variation in stiffness, the larger the change in strength. According to the fatigue load, the fatigue failure area of the concrete surrounding the stud shear connector increased, which caused the relative-slip to increase, which in turn resulted in a decrease in

residual strength.

4. The fatigue endurance of the stud satisfied the characteristic values of the Eurocode-4, AASHTO LRFD, and JSSC. Although more tests are required for confirmation, the design values specified in the codes are deemed to be applicable to design of the stud shear connectors for the new bridge deck system.

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References

Oehlers, D. J. and Bradford, M. A. (1999), *Elementary Behavior of Composite Steel & Concrete Structural Members.* Butterworth-Heinemannn, Oxford.

Johnson, R. P. (1994), *Composite Structures of Steel and Concrete*, Blackwell Scientific Publications, London.

Johnson, R. P. (2000), "Resistance of stud shear connectors to fatigue", *J. Constr. Steel Res.,* **56**, 101-116.

Viest, I. M. (1956), "Investigation of stud shear connectors for composite concrete and steel T-beams", *J. ACI*, **103**, 53-77.

Viest, I. M. (1960), "Review of research on composite steel-concrete beams", *J. Struct. Div.*, ASCE, 1-21.

Oehlers, D. J. and Foley, L. (1985), "The fatigue strength of stud shear connectors in composite beams", *Proc. Instn Civ. Engrs*, Part 2, **79**, 349-364.

Oehlers, D. J. and Johnson, R. P. (1987), "The strength of stud shear connectors in composite beams", *The Structural Engineer*, **65B**(2), 44-48.

Ellobody, E. and Lam, D. (2002), "Modeling of headed stud in steel-precast composite beams", *Steel Compos. Struct.,* **2**(5), 355-378.

Shim, C. S., Lee, P. G., Kim, H. H. and Yoon, T. Y. (2003), "Fatigue behavior of large diameter stud shear connectors, *J. Korea Society of Steel Constr.*, **15**(6), 621-628.

Hanswille, G., Porsch, M. and Üstündag, C. (2007), "Resistance of headed studs subjected to fatigue loading Part I: Experimental study", *J. Constr. Steel Res.*, **63**, 475-484.

Hanswille, G., Porsch, M. and Üstündag, C. (2007), "Resistance of headed studs subjected to fatigue loading Part II: Analytical study", *J. Constr. Steel Res.*, **63**, 485-493.

Eurocode-4 ENV (1997), *Design of Composite Steel and Concrete Structures,* European Committee for Standardization (CEN).

Jeong, Y. J., Kim, S. H. and Ahn, J. H. (2005), "Partial-interactive behavior of steel-concrete member under static and fatigue loadings", *Mag. Concrete Res.*, **57**(5), 289-300.

Jeong, Y. J., Jeong, G. H., Ku, H. B. and Kim, B. S. (2004), "Experimental properties of static behavior of steel-concrete composite bridge decks", *Journal of Korean Society of Civil Engineers*, **24**(1A), 17-25.

Korea Institute of Construction Technology (2005), *Development of a Long-life Deck System for Bridges (IV),* KICT 2005-057, Korea.

The Japanese Society of Steel Construction (1993), *Fatigue Design Recommendations for Steel Structures*, Gihodo Shuppan.

AASHTO LRFD (2004), *Bridge Design Specifications SI UNIT Third Edition*, Washington DC.

Ministry of Construction and Transportation (2005), *Design Specification for Highway Bridges,* Korea.

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